Why understanding neutrino interactions is important for oscillation physics

Christopher W. Walter

Department of Physics, Duke University, Durham, NC 27708 USA

Abstract.
Uncertainties in knowledge of neutrino interactions directly impact the ability to measure the parameters of neutrino oscillation. Experiments which make use of differing technologies and neutrino beams are sensitive to different uncertainties.

Keywords: Neutrino Interactions, Neutrino Oscillations
PACS: 13.15.+g, 14.60.Pq

INTRODUCTION

Strong evidence for neutrino oscillation and the existence of neutrino mass exists from atmospheric neutrinos [1], solar neutrinos [2, 3], reactor experiments [4], and long baseline oscillation experiments [5]. The recent results from the MiniBooNE experiment [6] have confirmed our standard model of neutrino oscillations. The picture of neutrino physics we have extracted is that there are three active neutrinos with two mass splittings. Of the three mixing angles needed to mix the three mass states together, two are large or near maximal and one is small and possibly zero.

Theoretical attempts to explain why the neutrino masses are so small and their mixings are large often rely on physics at the GUT scale (for a recent discussion see [7]). One of the most popular ideas, known as the See-Saw mechanism [8], coupled with CP violation in neutrinos produces leptogenesis [9], where a lepton matter/antimatter asymmetry caused by the decay of heavy neutrinos is converted into a baryon asymmetry and explains why today we live in a matter dominated universe. To explore these ideas there are a set of questions which need to be experimentally addressed. These are:

- What is the relative pattern of masses of the known neutrino mass differences?
- What is the size of the one neutrino mixing angle that has not been measured? Is it large enough to allow us to eventually measure the violation of CP if it exists?
- Do neutrino violate CP symmetry?
- Unlike quarks the neutrino mixing angles that have been measured are large, some possibly even maximal. Are the largest angles really maximal and what would that imply?

Unfortunately, we do not live in a world where we can cleanly interact neutrinos off of single quarks. Quarks come bundled inside of nucleons which themselves are found in the nucleus. For this reason, in order to extract the information about neutrino oscilla-

tions and masses we wish from our experiments, we must also understand the physics of neutrino interactions inside of nuclear material.

CROSS SECTIONS

Since the first NuInt01 meeting [10] we have made a lot of progress in this field. However, there are many outstanding questions, some of them quite basic. One example, which has been noted experimentally by both the K2K and MiniBooNE experiments, is the unexpected suppression at low Q^2 of charged-current quasi-elastic interactions. At this meeting we saw new work from the MiniBooNE collaboration to address this issue [See these proceedings].

There are also subtler effects that take place in the nucleus, some dependent on the type of nucleus the interaction takes place in. The neutrino interaction cross-sections are shown (along with some data) in figure 1 which is taken from [11].

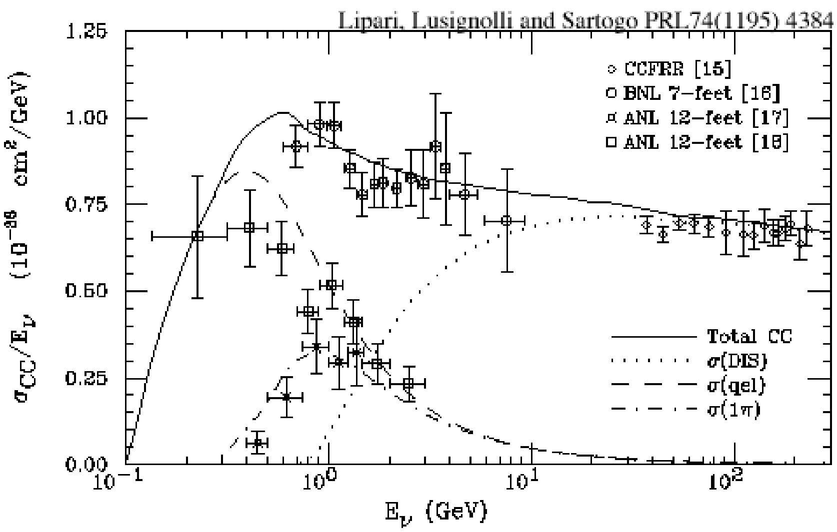

FIGURE 1. The neutrino nucleon cross section as a function of neutrino energy. Below 1 GeV the cross section is dominated by quasi-elastic interactions. For these interactions the neutrino energy can be reconstructed using only the outgoing lepton.

Different experiments sample different parts of this figure. For example, the T2K experiment [12] has a beam which is peaked below 1 GeV and is therefore dominated by quasi-elastic interactions. The NoVa [13] experiment on the other hand uses neutrinos in the few-GeV and above range.

An important way to mitigate the problems due to uncertainties in these cross-sections is to use both a near and far detector to measure the interactions before and after interactions. However, what is measured in each detector is the flux×cross-section and any differences in detector efficiency, flux, or cross-section between the two detectors will be convolved with the errors due to the nuclear effects and will not completely cancel.

The are several types of interaction uncertainties to consider, and which ones are important depend both on the detector technology being used, and the physics analysis being performed. Future experiments which wish to probe CP violation will also make use of anti-neutrino beams, and so we must understand the cross-sections of those anti-neutrinos on nuclear material as well. The first results from high statistics anti-neutrino running were shown by the MiniBooNE collaboration in this meeting [See these proceedings].

RECONSTRUCTING NEUTRINO EVENTS IN DETECTORS

Neutrino oscillation analyses can be broadly separated into two classes: searches for neutrino disappearance and appearance. In disappearance experiments, a neutrino flavor oscillates into another neutrino flavor for which there is not enough energy for a charged-current interaction to take place and produce a lepton. The measured effect is a distortion in the observed energy spectrum at the far detector. In an appearance experiment, one searches for the appearance of a flavor at the far detector which was not present in the initial beam. Different experiments use different techniques depending both on the detector technology used and the energy of the incoming neutrinos. Here, I touch on three illustrative examples which show uncertainties in neutrino interactions can affect oscillation results.

1. Reconstruction of the neutrino energy spectrum in large Water Cherenkov detectors.
2. Reconstruction of the neutrino energy spectrum in large calorimetric detectors.
3. Identification and reconstruction of tau neutrino events in large hybrid tracking/emulsion detectors.

Water Cherenkov detectors: the effect of non-QE interactions

Water Cherenkov detectors like Super-Kamiokande [14] achieve a large mass by using water both as a target and active detector element. However, because of the nature of the Cherenkov process not all particles produced in neutrino interactions are visible in a water Cherenkov detector. Fortunately, if the reaction is quasi-elastic(QE) the kinematics of the event and the incoming neutrino energy can be reconstructed using only the energy and angle with respect to the beam of the produced lepton. Equation 1 shows the relationship between the incoming neutrino energy and the reconstructed momentum of the produced lepton.

$$E_\nu = \frac{m_N E_\mu - m_u^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}, \tag{1}$$

Unfortunately, those events which are not due to quasi-elastic interactions will have their energies systematically underestimated. Figure 2 shows the effect on mis-reconstruction on an oscillation experiment.

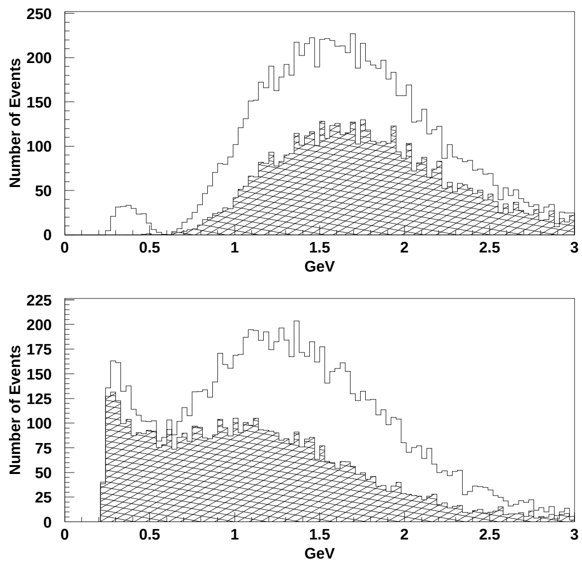

FIGURE 2. The top panel shows the Monte Carlo K2K spectrum at Super-K with oscillations applied. The oscillation dip at 700 MeV maximally suppresses the flux of ν_μ neutrinos. The non-QE interactions(hatched region) are un-effected by oscillations because their energy is too high. The bottom panel shows the same thing using reconstructed energy. The non-QE interactions "fill in" the oscillation dip.

For this reason, it is quite important to accurately model the fraction and shape of this non-QE "background". The parameter $\sin^2 2\theta$ determines the overall normalization of the oscillation suppression, with $\sin^2 2\theta$ =1 resulting in a complete suppression of the flux. If the amount of non-QE interactions is not-properly modeled, then the overall suppression in the oscillation region will not be modeled properly either, and the less than maximal suppression will be incorrectly interpreted as a $\sin^2 2\theta$ less than unity.

Calorimetric detectors: the effect of pion absorption

Large calorimetric detectors like MINOS [15] use a different reconstruction technique and are most sensitive to a different set of interaction uncertainties. One advantage of a colorimetric detectors relative to water Cherenkov detectors is that all of the particles are in principle visible. However, in order to range out the particles in high energy interactions heavy materials such as steel are often used. In the MINOS experiment a large fraction of the events come from deep inelastic scattering and in order to reconstruct the neutrino energy the energy of the outgoing lepton plus all pions and secondary particles in the shower must be added up. Equation 2 shows the relationship between the incoming neutrino energy and the reconstructed momentum of the produced lepton and energy of any associated shower,

$$E_\nu = E_\mu + E_{shower}. \tag{2}$$

This use of this technique means that any unaccounted for loss in energy of the shower will directly translate into an error on the reconstructed energy scale. The can happen as

pion are absorbed in the steel planes and within the iron nuclei themselves. This energy scale uncertainty caused by hadronic interactions is currently on the order of 10% in the MINOS experiment and is the second largest systematic error on the measured Δm^2. The effect on internuclear interactions in the MINOS experiment was nicely demonstrated my M. Kordoski at the NuInt05 meeting [16].

Tracking detectors: The effect of charm production

Hybrid emulsion tracking detectors like the OPERA experiment [17] face a very different set of problems and challenges. OPERA is an appearance experiment and is looking for the tell-tale kink of a tau decay in their emulsion. Tracking chambers are used to guide an automatic emulsion scanning system back to the vertex of the event. At this point a kinematic reconstruction and topological analysis is done to attempt to identify the small number of tau events expected in the sample.

The main backgrounds for this sort analysis include hadronic re-interactions which can cause kinks in tracks that look like decays and charm decays which can be misidentified as having tau-decay topology. Future decreases in the uncertainties in charm production cross-sections would decrease the uncertainty on this background.

MODELING INTERACTIONS IN THE NUCLEUS

All of the effects motioned above must be modeled in our neutrino interaction Monte Carlos. The previous examples were only a few of the effects that must be considered. Intense theoretical and modeling work is addressing a whole suite of issues in neutrino interaction physics. Many of these issues are addressed more fully in this volume. Due to lack of space, I only list many of the more relevant issues here:

- The modeling of the quasi-elastic cross-section and axial mass.
- New work on non-dipole nuclear form factors.
- Models of resonant and coherent pion production.
- Deep inelastic scattering and the transition to the resonance region.
- Proper modeling of final states due to the Pauli exclusion principle.
- The use of spectral functions to model binding energy and lepton momentum.
- The re-scattering of final state particles in the nucleus.
- The modification of parton distribution functions in the presence of other nucleons.

One item in this list above deserves special mention since it was the subject of intense discussion in this workshop. The K2K experiment has measured a striking deficit in the amount of charge-current coherent pion production [18]. The amount of neutral current production on the other hand seems to agree with the theoretical models. The amount of pion production in neutrino beams is of importance to the next generation of long-baseline experiments since mis-identified neutral pions are an important source of background in the search for electron neutrino appearance.

New theoretical work presented at this workshop can explain at least some of this deficit in the charged current channel by correctly incorporating the mass of the final state lepton in the calculations.

CONCLUSIONS

Uncertainties in neutrino interactions are a important source of systematic errors when trying to make precision measurements of neutrino oscillation parameters. Not only must the effects themselves be understood and properly modeled but the uncertainties on these effects need to be properly accounted for in analyses.

The NuInt series has been extremely important both in addressing these issues and in fostering new experimental collaborations. The new data we see in this meeting and we soon expect to see from dedicated interaction experiments will be a crucial piece of the world-wide effort to untangle the unknown physics of neutrino oscillations.

REFERENCES

1. Y. Ashie, et al., *Phys. Rev.* **D71**, 112005 (2005), `hep-ex/0501064`.
2. S. Fukuda, et al., *Phys. Lett.* **B539**, 179–187 (2002), `hep-ex/0205075`.
3. Q. R. Ahmad, et al., *Phys. Rev. Lett.* **89**, 011301 (2002), `nucl-ex/0204008`.
4. T. Araki, et al., *Phys. Rev. Lett.* **94**, 081801 (2005), `hep-ex/0406035`.
5. M. H. Ahn, et al., *Phys. Rev.* **D74**, 072003 (2006), `hep-ex/0606032`.
6. A. A. Aguilar-Arevalo, et al., *Phys. Rev. Lett.* **98**, 231801 (2007), `arXiv:0704.1500[hep-ex]`.
7. APS Joint Study on the Future of Neutrino Physics: The Neutrino Matrix (2005).
8. Gell-Man, Ramond, Slansky, and Yangida (1978).
9. M. Fukugita, and T. Yanagida, *Phys. Lett.* **B174**, 45 (1986).
10. Morfin, J. G. , and Sakuda, M. , and Suzuki, Y., editor, *Neutrino nucleus interactions in the few GeV region. Proceedings, 1st International Workshop, NuInt01,*, Tsukuba, Japan, 2001.
11. P. Lipari, M. Lusignoli, and F. Sartogo, *Phys. Rev. Lett.* **74**, 4384–4387 (1995), `hep-ph/9411341`.
12. Y. Itow, et al. (2001), `hep-ex/0106019`.
13. I. Ambats, et al. (2004), FERMILAB-PROPOSAL-0929.
14. Y. Fukuda, et al., *Nucl. Instrum. Meth.* **A501**, 418–462 (2003).
15. D. G. Michael, et al., *Phys. Rev. Lett.* **97**, 191801 (2006), `hep-ex/0607088`.
16. Cavanna, F. , and Morfin, J. G. , and Nakaya, T., editor, *NuInt05, proceedings of the 4th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region*, Okayama, Japan, 2005.
17. J. Marteau (2007), `arXiv:0706.1699[hep-ex]`.
18. M. Hasegawa, et al., *Phys. Rev. Lett.* **95**, 252301 (2005), `hep-ex/0506008`.